



**University of
Zurich**^{UZH}

**Zurich Open Repository and
Archive**

University of Zurich
University Library
Strickhofstrasse 39
CH-8057 Zurich
www.zora.uzh.ch

Year: 2011

Study of the electromagnetic background in the XENON100 experiment

XENON100 Collaboration ; Baudis, L ; Askin, A ; Aprile, E

Abstract: The XENON100 experiment, located at the Laboratori Nazionali del Gran Sasso, aims to directly detect dark matter in the form of weakly interacting massive particles via their elastic scattering off xenon nuclei. We present a comprehensive study of the predicted electronic recoil background coming from radioactive decays inside the detector and shield materials and intrinsic radioactivity in the liquid xenon. Based on GEANT4 Monte Carlo simulations using a detailed geometry together with the measured radioactivity of all detector components, we predict an electronic recoil background in the energy region of interest and 30 kg fiducial mass of less than 10^{-2} events \cdot kg $^{-1}$ \cdot day $^{-1}$ \cdot keV $^{-1}$, consistent with the experiment's design goal. The predicted background spectrum is in very good agreement with the data taken during the commissioning of the detector in Fall 2009. © 2011 American Physical Society

DOI: <https://doi.org/10.1103/PhysRevD.83.082001>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-58267>

Journal Article

Accepted Version

Originally published at:

XENON100 Collaboration; Baudis, L; Askin, A; Aprile, E (2011). Study of the electromagnetic background in the XENON100 experiment. *Physical Review D*, 84(5):082001.

DOI: <https://doi.org/10.1103/PhysRevD.83.082001>

A study of the electromagnetic background in the XENON100 experiment

E. Aprile,¹ K. Arisaka,² F. Arneodo,³ A. Askin,⁴ L. Baudis,⁴ A. Behrens,⁴ K. Bokeloh,⁵ E. Brown,^{2,5} J.M.R. Cardoso,⁶ B. Choi,¹ D. Cline,² S. Fattori,^{3,7} A.D. Ferella,⁴ K.-L. Giboni,¹ A. Kish,^{4,*} C.W. Lam,² J. Lamblin,⁸ R.F. Lang,¹ K.E. Lim,¹ Q. Lin,⁹ S. Lindemann,¹⁰ M. Lindner,¹⁰ J.A.M. Lopes,⁶ K. Lung,² T. Marrodán Undagoitia,⁴ Y. Mei,¹¹ A.J. Melgarejo Fernandez,¹ K. Ni,⁹ U. Oberlack,^{7,11} S.E.A. Orrigo,⁶ E. Pantic,² G. Plante,¹ A.C.C. Ribeiro,⁶ R. Santorelli,⁴ J.M.F. dos Santos,⁶ M. Schumann,^{4,11} P. Shagin,¹¹ H. Simgen,¹⁰ A. Teymourian,² D. Thers,⁸ E. Tziaferi,⁴ H. Wang,² M. Weber,¹⁰ and C. Weinheimer⁵

¹*Department of Physics, Columbia University, New York, NY 10027, USA*

²*Physics & Astronomy Department, University of California, Los Angeles, USA*

³*INFN, Laboratori Nazionali del Gran Sasso, Assergi, 67100, Italy*

⁴*Physics Institute, University of Zürich, Winterthurerstrasse 190, CH-8057, Zürich, Switzerland*

⁵*Institut für Kerphysik, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany*

⁶*Department of Physics, University of Coimbra, R.Larga, 3004-516, Coimbra, Portugal*

⁷*Institute of Physics, Johannes Gutenberg University Mainz, 55128 Mainz, Germany*

⁸*SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS/IN2P3, Nantes, France*

⁹*Department of Physics, Shanghai Jiao Tong University, Shanghai, 200240, China*

¹⁰*Max Planck Institute for Nuclear Physics, Heidelberg, Germany*

¹¹*Department of Physics and Astronomy, Rice University, Houston, TX 77005 - 1892, USA*

The XENON100 experiment, located at the Laboratori Nazionali del Gran Sasso (LNGS), aims to directly detect dark matter in the form of Weakly Interacting Massive Particles (WIMPs) via their elastic scattering off xenon nuclei. We present a comprehensive study of the predicted electronic recoil background coming from radioactive decays inside the detector and shield materials, and intrinsic contamination. Based on GEANT4 Monte Carlo simulations using a detailed geometry together with the measured radioactivity of all detector components, we predict an electronic recoil background in the WIMP-search energy range (0-100 keV) in the 30 kg fiducial mass of less than 10^{-2} events \cdot kg $^{-1}\cdot$ day $^{-1}\cdot$ keV $^{-1}$, consistent with the experiment's design goal. The predicted background spectrum is in very good agreement with the data taken during the commissioning of the detector, in Fall 2009.

PACS numbers: 95.35.+d, 29.40.-n, 34.80.Dp

I. INTRODUCTION

For all experiments dealing with very low signal rates, such as dark matter or double beta decay searches, the reduction and discrimination of the background is one of the most important and difficult tasks. As the sensitivity of these experiments keeps increasing, the fight against the background remains crucial.

The XENON100 detector, which is installed in the Laboratori Nazionali del Gran Sasso (LNGS), Italy, is the second generation detector within the XENON program, dedicated to the direct detection of particle dark matter in the form of Weakly Interacting Massive Particles (WIMPs) [1]. It is the successor of XENON10 [2], which has set some of the best limits on WIMP-nucleon scattering cross-sections [3, 4]. XENON100 allows to improve this sensitivity due to an increase of the target mass and a significant reduction of the background in the target volume.

In the standard scenario, WIMPs are expected to elastically scatter off xenon nuclei resulting in low energy nu-

clear recoils (keV scale). Neutrons passing through the detector also produce nuclear recoils of similar energy, whereas gamma rays and electrons produce electronic recoils. This opens the possibility to efficiently reject the electromagnetic background using various discrimination techniques. Experiments like XENON10 distinguish electronic interactions from nuclear recoils based on a different ratio in the yield of scintillation light (primary signal, S1) and ionization charge (secondary signal, S2). Using this discrimination technique, XENON10 and XENON100 reached an electronic recoil rejection efficiency better than 99% at 50% nuclear recoil acceptance [3, 5].

The main sources of electronic recoil background in XENON100 are radioactive contamination of the materials used to construct the detector and the shield, intrinsic radioactive contamination in the LXe target, and the decays of ^{222}Rn and its progeny inside the detector shield. Even if the electronic recoil rejection efficiency, based on the ratio of the scintillation and ionization signals, is high, a potential statistical leakage of electronic recoil events into the nuclear recoil region can mimic a dark matter signal. One way to handle this background is a well-planned detector design avoiding the presence of radioactive materials close to the active volume. For XENON100, the design was supported by an a-priori se-

*Corresponding author; Electronic address:
alexkish@physik.uzh.ch

lection of low-background materials for all detector components and by surrounding the target volume with an active veto LXe veto. The use of passive shield, the same as developed for XENON10 but with several improvements, complemented the effort.

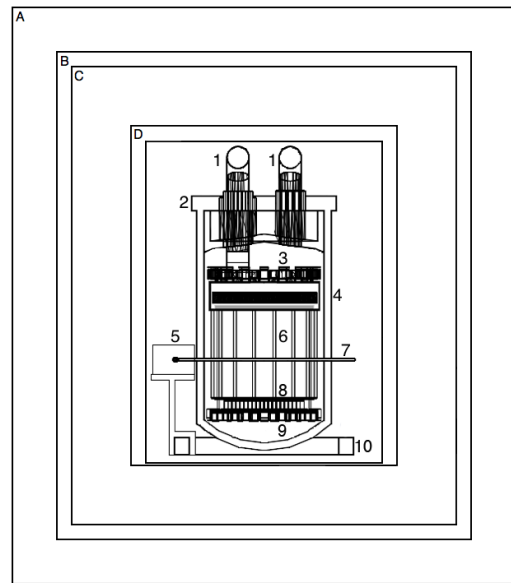
In this paper we summarize the effort to use extensive Monte Carlo simulations to predict the electronic background of XENON100 from natural radioactivity in the detector and shield components, and to study the background reduction by applying fiducial volume and veto coincidence cuts. Section II describes the detector model which has been used in the simulations. In Section III a brief overview on the radioactivity screening of the detector and shield materials used in XENON100 is given. The predicted electronic recoil background from the detector and shield materials is discussed in Section IV, the background from the decays of ^{222}Rn and its progenies in the shield cavity in Section V, and the background from the intrinsic contamination of radon and krypton in LXe in Section VI. The comparison of the background model with the measured background spectrum is presented in Section VII, and conclusions are drawn in Section VIII.

II. XENON100 DETECTOR DESIGN AND MODEL SIMULATED WITH THE GEANT4 TOOLKIT

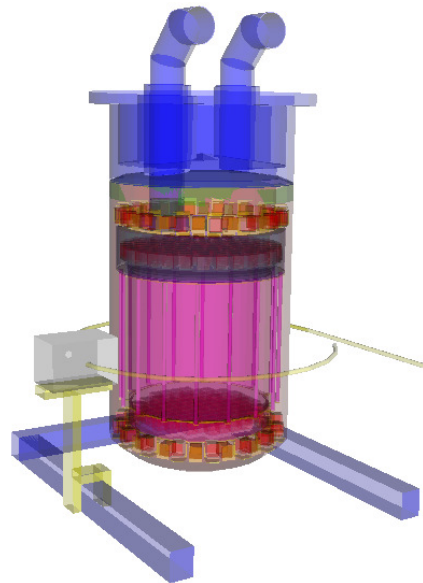
The XENON100 detector is a dual phase (liquid-gas) time-projection chamber (TPC). The total amount of LXe in the stainless steel (SS), vacuum insulated, detector's vessel is 161 kg. Of these, 62 kg are in the target volume, defined by a structure made from polytetrafluoroethylene (PTFE, *Teflon*) and copper. The target volume is viewed by two arrays of photomultiplier tubes (PMT), one on the bottom immersed in LXe, and one in the gas phase above the target volume. The electric fields in the TPC are generated by applying potential differences across electrodes, which include a cathode mesh installed above the bottom PMT array and a stack of three meshes around the liquid-gas interface. The electrodes are made of metal meshes to transmit the scintillation light produced by particle interactions in the target volume.

In order to simulate the response of the detector to various types of particles and to predict the intrinsic and ambient electronic recoil background, a detailed model (Figure 1) has been created with the Geant4 toolkit [6]. Table I shows the amount of materials used for the detector construction, computed from the model and in agreement with the actual detector.

The passive shield, with 4π coverage of the detector (Figure 1), is installed on a 25 cm polyethylene slab (not shown). It consists (from outside to inside) of tanks filled with water (thickness 20 cm, not shown) to shield against ambient neutrons, placed on 4 sides of the shield box, the door and the floor are not covered. After the water shield, there are two layers of lead (a 15 cm outer layer and a



(a)



(b)

FIG. 1: (a) The mass model of the XENON100 detector and its shield, as simulated with GEANT4: A - outer lead layer, B - inner lead layer with low ^{210}Pb contamination, C - polyethylene shield, D - copper shield; 1 - pipes to the PMT feedthroughs and pumping ports, 2 - stainless steel cryostat, 3 - top PMT array in the veto, 4 - top PMT array in the TPC (inside the 'diving bell' in the gas phase), 5 - lead brick for calibration with $^{241}\text{AmBe}$ neutron source, 6 - TPC wall (PTFE panels), 7 - copper pipe for calibration sources, 8 - bottom PMT array in the TPC, 9 - bottom PMT array in the veto, 10 - support bars for the cryostat. The water shield and an additional polyethylene layer on the bottom are not shown. (b) (Color online) 3D GEANT4 model of the XENON100 detector. The color shows: blue - ^{316}Ti SS, yellow - copper, magenta - PTFE, red - PMTs.

TABLE I: Materials used to construct the XENON100 detector and shield, and their radioactive contamination from measurements at underground facilities at LNGS [13]. The cryostat vessels with the top flange and pipes, and the 'diving bell' system are made from the ^{316}Ti SS and shown as one unit. The resistive voltage divider network for the TPC drift field is simplified in the model with a thin tube. The PMT bases made from *Cirlex* have been screened fully assembled, with the resistors and capacitors.

Component	Amount	Total radioactive contamination in materials [mBq/amount]				
		^{238}U	^{232}Th	^{60}Co	^{40}K	other nuclides
Cryostat and 'diving bell' (^{316}Ti SS)	73.6 kg	< 130	< 140	400±40	< 660	^{137}Cs : < 190
Support bars (^{316}Ti SS)	49.7 kg	< 65	140±30	700±20	< 350	
Detector PTFE	11.86 kg	< 0.7	< 1.2	< 0.4	< 8.9	
Detector copper	3.9 kg	< 0.86	< 0.62	0.78±0.31	< 5.2	
PMTs	242 pcs	36±5	41±10	150±20	2700±500	
PMT bases	242 pcs	39±5	17±5	<2.42	<39	
TPC resistor chain	1.47 g	1.1±0.2	0.57±0.12	< 0.12	7.8±1.2	
Bottom electrodes (^{316}Ti SS)	225 g	0.81±0.06	0.39±0.04	1.6±1.0	< 1.1	
Top electrodes (^{316}Ti SS)	236 g	< 0.64	< 0.35	3.1±0.2	< 2.8	
PMT cables	1.8 kg	< 2.9	6.7±3.2	< 1.2	63±23	
Copper shield	2.1 t	170±50	25±11	82±12	6.7±2.1	^{108m}Ag : 9.0±1.6 ^{210}Pb : (1.7±0.4)×10 ⁸ ^{210}Pb : (1.4±0.2)×10 ¹⁰
Polyethylene shield	1.6 t	370±80	< 150	-	1100±600	
Lead shield (inner layer)	6.6 t	< 4400	< 3600	< 730	< 9600	
Lead shield (outer layer)	27.2 t	< 25000	< 19600	< 3300	380±80	

5 cm inner layer with lower contamination of the radioactive isotope ^{210}Pb , see Table I), 20 cm of polyethylene, and the innermost 5 cm thick (0.5 cm on the bottom) copper layer. The copper reduces the gamma background from the outer shield layers. Highly radioactive detector components are mounted outside of the shield, for example signal and high voltage feedthroughs, vacuum pumps, pressure sensors and associated electronics. An innovative detector design feature, which has contributed to the low background rate of XENON100, is the mounting of the cryogenics system, based on a pulse tube refrigerator, outside the passive shield, far from the target volume.

The cylindrical TPC is formed by 24 interlocking PTFE panels. PTFE reflects scintillation light with high efficiency for vacuum ultraviolet [7], and optically separates the 62 kg target volume from the surrounding LXe, which has a mass of 99 kg (~ 4 cm thick). This allows to exploit the self-shielding capability of LXe due to its high density and high atomic number (2.83 g/cm³ at 182 K, 2.3 atm; $Z=54$; the mean free path of a 1 MeV gamma in LXe is 6.0 cm). In addition, this LXe volume around the target is instrumented with light sensors, becoming an active veto for background reduction by rejecting events in which a particle deposits part of its energy in the veto volume.

The TPC is enclosed in a double-walled, low activity ^{316}Ti SS cryostat supported inside the shield by SS bars ('support bars') which are mounted onto the movable shield door. The thickness of the inner and outer cryostat walls is 1.5 mm and the total weight of the vessel is 70.0 kg, which is only 30% of that of the XENON10 detector's cryostat [2]. The inner vessel containing the LXe is lined on the walls and the bottom with a PTFE layer (1.5 mm thick) in order to increase the light collection efficiency in the active veto volume.

The gas phase for charge amplification is maintained by the use of a SS 'diving bell' system (weight 3.6 kg). It allows to keep the liquid level constant at a precise height while having an additional layer of LXe above the TPC.

Electrons created by ionization in the LXe target are drifted upwards by a strong electric field created by applying voltage on the cathode. In order to shield the bottom PMTs from this electric field, an additional grounded mesh is installed below the cathode. The anode mesh, sandwiched between two grounded meshes, is placed inside the 'diving bell'. An extraction field is created across the liquid-gas interface by applying high voltage on the anode. Two additional meshes are installed below (gate grid) and above (top mesh) the anode and kept at ground potential in order to close the field cage and shield the top PMT array from the high electric field. Ionization electrons are drifted, extracted into the gas phase, and accelerated, producing the proportional scintillation (S2) signal [9]. The gaps between the electrodes (gate - anode and anode - top mesh) are 5 mm, and the liquid level is adjusted between the gate and anode grids. In the background model, only the SS support rings for the meshes are considered, given that the meshes themselves have a very low mass, leading to a negligible background from their radioactive contamination. To optimize the uniformity of the drift field inside the TPC, 40 equidistant field shaping rings made of copper wires are used. They are connected through a voltage divider network which consists of 41 resistors. These are simplified in the Monte Carlo model with a thin tube with equal total mass.

The prompt (S1) and the proportional scintillation light (S2) generated by particles interacting with Xe atoms is detected by 242 1"-square R8520-06-AL Hamamatsu PMTs, which are among the lowest activity

PMTs, and are optimized to operate in LXe (temperature ~ 182 K, scintillation light wavelength 178 nm [10]). The top PMT array consists of 98 PMTs, mounted in a concentric pattern in a PTFE support structure inside the SS 'diving bell'. The bottom PMT array consists of 80 PMTs, mounted below the cathode in the LXe, and arranged in a rectangular pattern in order to maximize the photocathode coverage. Additionally, 64 PMTs view LXe of the veto volume: 16 PMTs above and below the TPC, and 32 observing the sides. The PMT is shown in Table II. In the GEANT4 model, a PMT is simplified with a SS case and a synthetic silica window inside a thin aluminum ring. A PMT is supplied with high voltage through the voltage divider circuit mounted on a base made from *Cirlex*. The base is approximated in the model as a homogenous unit.

TABLE II: Mass model of the R8520-06-AL PMT [8]. The last two materials are not included in the Geant4 model due to their low mass.

PMT part	Material	Weight [g]
Metal package and stem pins	Kovar metal	13
Electrodes	stainless steel	7
Glass for window	synthetic silica	2
Glass in stem	borosilicate glass	1
Aluminum ring	Al	0.1
Insulator	ceramic	0.04
Getter	ZrAl	0.02

The XENON100 data acquisition system (DAQ) digitizes the full waveform of the 242 PMTs at 100 MHz, where the time window for an event is $400 \mu\text{s}$ (more than twice the maximum drift time). If a particle has deposited energy at multiple places in the target, then two or more S2 pulses are recorded in the trace. Such an event is a multiple scatter event and is rejected in the analysis since the predicted behavior of the WIMP, due to its very low scattering cross-section, is a single scatter event.

For the calculation of the final background rate in the Monte Carlo simulations, multiple scatter events are rejected taking into account the finite position resolution of the detector. Multiple scatter event is considered as a single scatter event if the interactions happen less than 3 mm apart in Z . This position resolution is given by the width of the S2 signals and the peak separation efficiency of the S2 peak finder algorithm.

III. MATERIAL SCREENING

Special care has been taken to select detector and shield materials according to their radioactive contamination. Before detector construction, the majority of materials planned to be used were screened with low background Ge detectors in order to determine their intrinsic radioactivity, mostly due to residual ^{238}U , ^{232}Th , ^{40}K , and ^{60}Co contamination. XENON has access to a

dedicated screening facility underground at LNGS (the Gator detector [11]). Moreover, the LNGS screening facility, with some of the most sensitive Ge detectors in the world [12], has also been used. The radioactive contamination of the materials used for detector construction is shown in Table I. For more details, see reference [13]. The measured activities are used as an input information for the Monte Carlo simulations and background predictions, as described in the following sections. For the analysis presented here, the upper limits are as detection values.

IV. BACKGROUND DUE TO RADIOACTIVE CONTAMINATION IN THE DETECTOR AND SHIELD MATERIALS

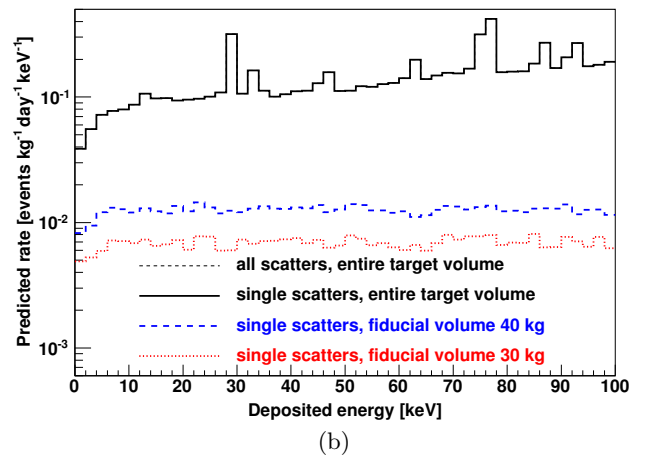
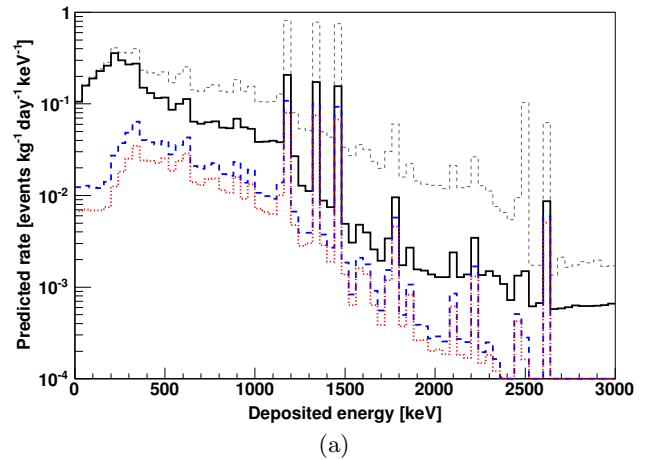


FIG. 2: (a) (Color online) Energy spectra of all events (thin dashed line) and single scatters (solid line) in the target volume (62 kg of LXe), and single scatters in the 40 kg (thick dashed line) and 30 kg fiducial volumes (dotted line), with infinite energy resolution. (b) (Color online) Zoom into the low energy range of the spectra (0-100 keV). The spectra of all scatters and single scatter events in the entire target volume overlap.

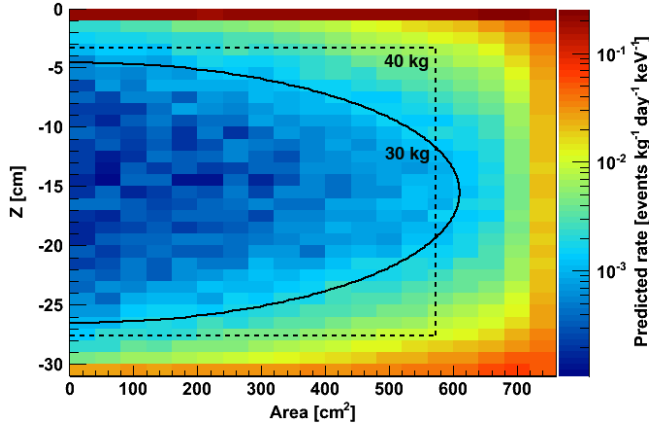


FIG. 3: (Color online) Predicted electronic recoil background from detector and shield materials, excluding contamination of ^{85}Kr and ^{222}Rn in LXe. Shown are single scatter events in the energy region of interest (0-100 keV) in the TPC, without veto cut. $Z = 0$ cm corresponds to the liquid-gas interface. The cathode mesh is located at $Z = -304.5$ mm. The dashed line shows the 40 kg fiducial volume, and the solid line illustrates the 30 kg fiducial volume optimized on the background expectation.

Decays of the radioactive isotopes in the materials listed in Table I have been simulated within the GEANT4 framework and the corresponding background rates have been calculated.

The energy range for the background rate calculation is chosen to be sufficiently wide (up to 100 keV), to include the signal region for inelastic dark matter which is predicted to be in a higher energy range than the one from standard elastic WIMP scattering [14]. Figure 2 shows the spectra in the entire energy range (a) and in the region of interest, below 100 keV (b). The effect of the discrimination between multiple and single scatter events on the background rate can be seen in Figure 2 (a): the multiple scatter behavior of incident gamma rays is typical for higher energies, whereas single scatter events dominate in the low energy region, and the multiple scatter cut does not yield a significant reduction of the background rate. Further background reduction can be achieved with fiducial volume cuts.

In Figure 2 (b) several characteristic X-rays can be seen. The xenon K-shell fluorescence peaks appear at 30 keV and 34 keV. The X-ray peaks at 15, 75, 85 and 90 keV are from Pb and Bi close to the target volume (i.e., in PTFE walls). In addition, there is a 46 keV gamma line from ^{210}Pb decay, and 63 keV gamma line from the decay of ^{234}Th . Due to their short mean free path, these low energy lines can be observed only at the edge of the LXe volume. After applying a cut on the position of the interactions, the peaks disappear and the spectrum becomes relatively flat in the low energy region (at least up to ~ 100 keV). The background rate is thus presented as the average from 0 to 100 keV.

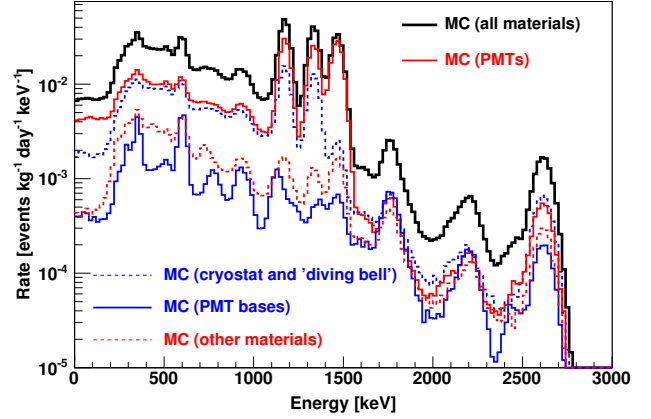


FIG. 4: (Color online) The predicted background from the detector and shield materials (thick black line), in the 30 kg fiducial mass without veto cut, together with the individual contributions from the PMTs (red solid line), the SS cryostat with pipes and 'diving bell' (blue dashed line), PMT bases (blue solid line). Red dashed line shows the background from all other materials: detector PTFE and copper, SS cryostat support bars, TPC resistor chain, top and bottom electrodes, PMT cables, and copper and polyethylene shield. The measured energy resolution is taken into account.

Table III presents the upper limits on the average single scatter electronic recoil rates from detector materials in the energy region of interest. The background rate has been predicted for the entire target volume (62 kg), and for two fiducial volumes: a simple 40 kg cylindrical fiducial volume used in the analysis of the first XENON100 data [5], and a 30 kg fiducial volume cut optimized on the background expectation.

The spatial distribution of the single scatter electronic

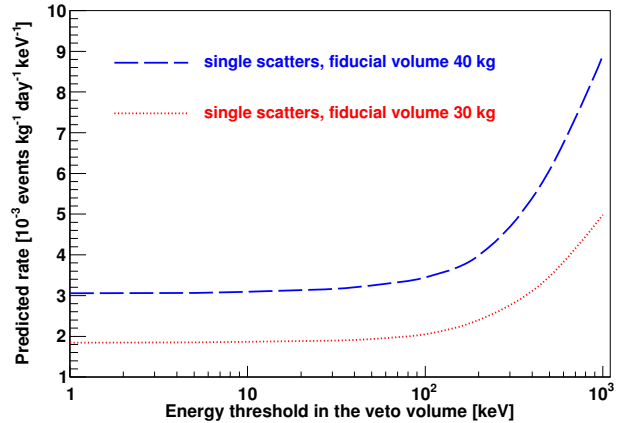


FIG. 5: (Color online) Predicted background rate from the detector and shield materials in the energy range 0-100 keV, as a function of the energy threshold in the active veto. The average energy threshold in the veto measured with a collimated ^{137}Cs source is about 100 keV.

recoils in this region is presented in Figure 3. The radial cut rejects events at the edge of the target volume, originating mostly from radioactive decays in the PTFE of the TPC and the SS of the cryostat vessels. The background from the PMTs, PMT bases, 'diving bell', and the electrode meshes can be efficiently reduced by rejecting events within the top and bottom layers of LXe.

The Monte Carlo spectrum of the background from the detector and shield materials is shown in Figure 4, for the 30 kg fiducial mass without veto cut. The energy resolution measured with the calibration sources is taken into account (for details see Section VII). The background in the energy region of interest, from 0 to 100 keV, is dominated by the PMTs ($\sim 65\%$ of the total background from all detector and shield materials), and the SS cryostat, pipes and 'diving bell' (other $\sim 25\%$). The dominant contribution to the background from the PMTs is originating from the ^{60}Co and ^{40}K contamination (50% and 34%, respectively). The main contaminant in the SS is ^{60}Co , which is responsible for almost 70% of the total background from this material.

The effect of the active LXe veto is presented in Figure 5, showing the total rate as a function of the energy threshold in the veto volume. The active veto (with an energy threshold of about 100 keV, which is the average threshold measured with a collimated ^{137}Cs source) allows to reduce the background rate in the entire target volume by 50%. Background reduction is even more efficient if the veto cut is combined with a fiducial volume cut, which results in a $>90\%$ reduction of the background rate. The reduction of the background rate remains almost constant when the energy threshold in the veto is below ~ 100 keV. This is explained by an anti-correlation of the energy deposition in the active veto and target volume: events that deposit a small amount of energy in the target volume are likely to have deposited a larger amount of energy in the veto volume.

V. BACKGROUND FROM ^{222}Rn DECAYS IN THE SHIELD CAVITY

A potentially dangerous background for XENON100 is the gamma background from the decay of ^{222}Rn daughters (half-life of 3.8 days) inside the shield cavity (volume 0.58 m^3). The average measured radon activity in the LNGS tunnel at the location of the experiment is 200-300 Bq/m^3 . Therefore, the cavity is constantly flushed with nitrogen gas when the shield door is closed. Nevertheless, a certain amount of radon can still be present. The ^{222}Rn activity and the trigger rate of the DAQ system are shown for an early commissioning stage in Figure 6. A clear correlation can be seen between the two parameters, which lead to an improvement of the shield sealing and an increase of the N_2 purge flow. During the science runs, a low and constant ^{222}Rn concentration is kept inside the shield ($<1\text{ Bq/m}^3$ as measured with a dedicated radon monitor).

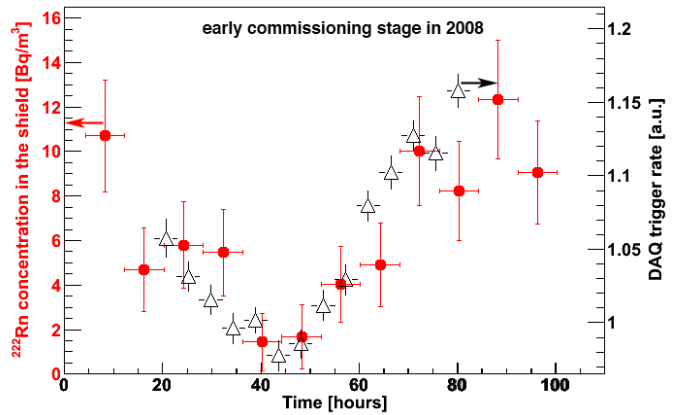


FIG. 6: (Color online) Measured correlation of the ^{222}Rn activity in the shield cavity (circles) and the DAQ trigger rate (triangles) during an early commissioning stage in 2008. ^{222}Rn level of $<1\text{ Bq/m}^3$ is kept during science runs.

Figure 7 presents the predicted background rate due to ^{222}Rn as a function of radon concentration inside the shield. For 1 Bq/m^3 of ^{222}Rn it is $6 \times 10^{-3}\text{ events}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ when the entire target volume (62 kg of LXe) is considered, $9 \times 10^{-4}\text{ events}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ in the 40 kg fiducial volume, and $2 \times 10^{-4}\text{ events}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ in the 30 kg fiducial volume. For the 30 kg fiducial volume, this is $<10\%$ of the background contribution from the detector and shield materials.

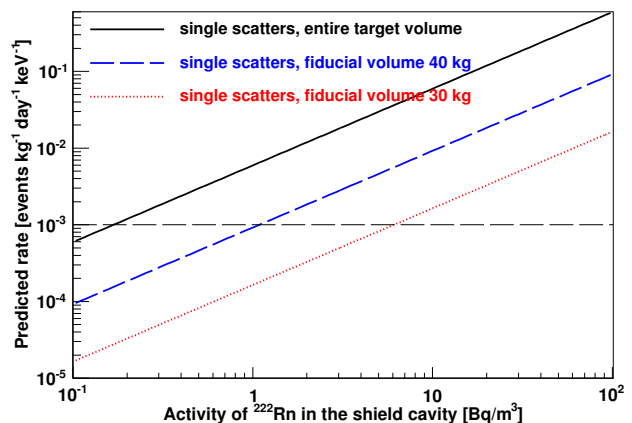


FIG. 7: (Color online) Predicted rate of single electronic recoils in the energy range 0-100 keV as a function of ^{222}Rn concentration in the shield cavity for different fiducial masses. As a reference value, the horizontal dashed line corresponds to a background rate of $10^{-3}\text{ events}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$.

TABLE III: Predicted rate of single electronic recoils in the energy range 0-100 keV, in the entire target volume and in 40 kg and 30 kg fiducial volumes, with and without veto cut (energy threshold 100 keV). The statistical errors of the simulation are less than 1%. The background from the support rings for the anode stack meshes is relatively high, but only within a few mm near the liquid-gas interface, hence it can be sufficiently reduced with the fiducial volume cuts. The background from the lead shield is negligible.

Volume	Single electronic recoils [$\times 10^{-3}$ events \cdot kg $^{-1}\cdot$ day $^{-1}\cdot$ keV $^{-1}$]					
	target (62 kg)		fiducial (40 kg)		fiducial (30 kg)	
Veto cut	none	active	none	active	none	active
Cryostat and 'diving bell' (^{316}Ti SS)	20.90	6.70	2.62	0.65	1.81	0.48
Support bars (^{316}Ti SS)	1.00	0.24	0.19	0.05	0.13	0.04
Detector PTFE	3.50	2.90	0.05	1.3×10^{-2}	3.4×10^{-2}	1.0×10^{-3}
Detector copper	0.31	0.13	0.02	4.7×10^{-3}	1.2×10^{-2}	2.6×10^{-3}
PMTs	81.6	44.5	8.84	2.40	4.61	1.32
PMT bases	15.9	10.3	0.86	0.22	0.40	0.12
TPC resistor chain	1.7×10^{-4}	1.2×10^{-4}	2.7×10^{-6}	7.1×10^{-7}	2.1×10^{-6}	5.7×10^{-7}
Bottom electrodes (^{316}Ti SS)	0.24	0.12	0.01	2.1×10^{-3}	6×10^{-3}	1.4×10^{-3}
Top electrodes (^{316}Ti SS)	11.80	9.90	0.03	7.0×10^{-3}	0.02	4.6×10^{-3}
PMT cables	0.56	0.08	0.10	0.02	0.08	0.02
Copper shield	0.64	0.22	0.10	0.04	0.07	0.02
Polyethylene shield	0.33	0.09	0.05	0.01	0.03	0.01
Total	136.8	75.2	12.9	3.4	7.2	2.0

VI. BACKGROUND DUE TO INTRINSIC KRYPTON AND RADON CONTAMINATION

There is no long-lived radioactive xenon isotope, with the exception of the potential double beta emitter ^{136}Xe , with the half-life limits of $>7 \times 10^{23}$ years and $>1.1 \times 10^{22}$ years for the neutrinoless and 2ν double beta decay, respectively [15]. Given this limit, the background rate from 2ν double beta decay of ^{136}Xe in the WIMP-search energy range (0-100keV) is $<10^{-4}$ events \cdot kg $^{-1}\cdot$ day $^{-1}\cdot$ keV $^{-1}$, as shown in Figure 10, thus it is not considered dangerous for the sensitivity of

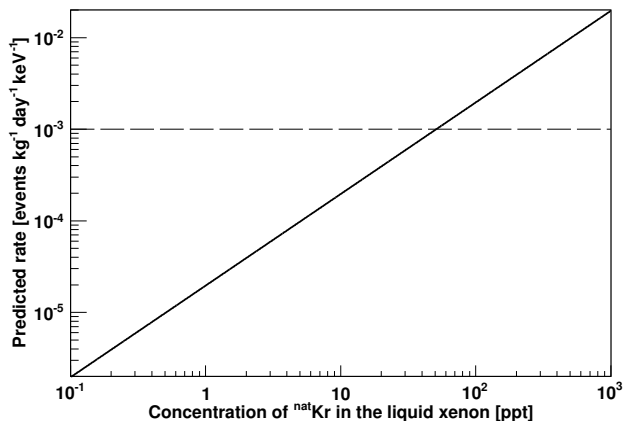


FIG. 8: Rate of single electronic recoils from ^{85}Kr decay in the energy range 0-100 keV as a function of the concentration of natural Kr in the LXe. Fiducial and veto cuts are inefficient for this intrinsic background source. As a reference value, the horizontal dashed line corresponds to a background rate of 10^{-3} events \cdot kg $^{-1}\cdot$ day $^{-1}\cdot$ keV $^{-1}$.

the XENON100 experiment.

Commercially available xenon gas, where purification is performed by distillation and adsorption-based chromatography, has a contamination of natural krypton at the ppm level. Natural krypton contains about 10^{-11} g/g of radioactive ^{85}Kr . The background from the beta decay of ^{85}Kr ($T_{1/2} = 10.76$ years, endpoint energy 687 keV with a branching ratio 99.563%) is a potentially serious limitation in the sensitivity of rare-event searches using xenon targets.

The gas used in the XENON100 experiment has been processed at a commercial distillation plant to reduce the concentration of krypton to <10 ppb. The high-temperature getter used in the experiment to purify xenon from water and electronegative contaminants does not remove the noble gas krypton. Therefore, an additional gas purification has been performed with a cryogenic distillation column.

Levels of radioactive trace contaminations in xenon might vary at different stages of the experiment, as they strongly depend on purification processes. The background rate from radioactive contamination in LXe has thus been predicted for different concentrations of ^{nat}Kr in LXe, and is shown in Figure 8.

Another intrinsic source of background is the decay of ^{222}Rn daughters in the LXe. Radon is present in the LXe due to emanation from detector materials and the getter, and diffusion of the gas through the seals.

In the Monte Carlo simulation, ^{222}Rn decays are generated uniformly in the LXe, and only the part of the chain before ^{210}Pb is considered, since the relatively long half-life time of 22.3 years for ^{210}Pb results in radioactive disequilibrium in the decay chain. The predicted background rate in the energy region 0-100 keV is shown in Figure 9 as a function of the ^{222}Rn concentration in the

LXe.

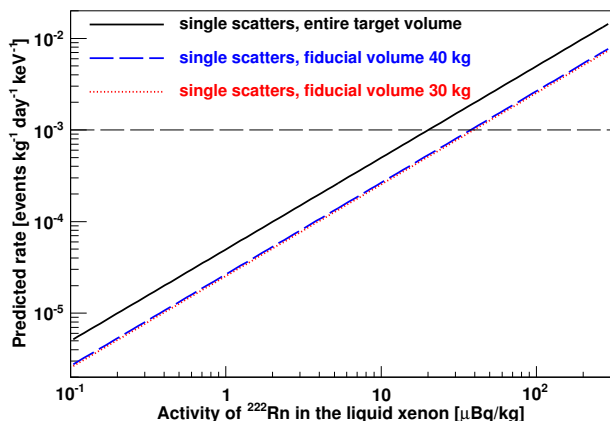


FIG. 9: (Color online) Predicted background rate (0-100 keV) as a function of ^{222}Rn concentration in the LXe. As a reference value, the horizontal dashed line corresponds to a background rate of 10^{-3} events $\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$.

A background contribution from each intrinsic radioactive contaminant of less than 10^{-3} events $\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ (used as a reference value) translates into a concentration of ^{nat}Kr below 50 ppt, and an activity of ^{222}Rn in LXe of <20 $\mu\text{Bq/kg}$ in the entire target volume (62 kg). The background from ^{222}Rn daughters in the LXe can be reduced by a fiducial volume cut, removing decays at the edge of the target volume which are likely to produce high energy gamma rays with a longer mean free path which escape the target volume. For the 40 kg and 30 kg fiducial volumes, the activity corresponding to 10^{-3} events $\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ is 35 $\mu\text{Bq/kg}$.

VII. COMPARISON OF THE PREDICTIONS WITH THE MEASURED DATA

During the first XENON100 science run (run_07, fall 2009) [5], the contamination of natural krypton in the LXe has been measured with a delayed coincidence analysis using a decay channel (branching ratio 0.434%) where ^{85}Kr undergoes a beta-decay with $E_{max} = 173.4$ keV to ^{85m}Rb ($\tau = 1.46$ μs), which in turn decays to the ground state emitting a gamma-ray with an energy of 514 keV. The concentration of ^{nat}Kr in the LXe determined with this technique is (143_{-90}^{+130}) ppt (mol/mol), assuming ^{85}Kr abundance of 10^{-11} . This concentration can be reduced by further purification.

For run_07, the ^{222}Rn contamination in the LXe has been determined using a beta-alpha time coincidence analysis, where events corresponding to the decays of ^{214}Bi ($T_{1/2} = 19.7$ min, $E_{max} = 3.27$ MeV) and ^{214}Po ($T_{1/2} = 164$ μs , $E_{\alpha} = 7.69$ MeV) are tagged. Based on this analysis, the upper limit on the ^{222}Rn activity in

LXe is <21 $\mu\text{Bq/kg}$.

The comparison of the background spectrum measured in run_07 [5] and the Monte Carlo simulation is shown in Figure 10, for the 30 kg fiducial volume without veto cut. For optimal energy resolution and improved linearity, the energy scale of the measured spectrum exploits the anti-correlation between the light and the charge [16]: $S1$ and $S2$ are combined according to $E = S1/4.4 + S2/132.6$ [keV]. The simulated spectrum is smeared with a Gaussian function using the energy resolution measured with calibration sources: $\frac{\sigma(E)}{E} = 0.009 + 0.485/\sqrt{E}$ [keV]. The contribution from the detector and shield materials is scaled based on the screening values shown in Table I. For the contamination of ^{222}Rn in the shield cavity we used the value measured with a dedicated radon monitor. Finally, for the ^{85}Kr and ^{222}Rn contaminations in the LXe we used the values determined with the delayed coincidence analyses described above. The upper limits from materials screening are used as fixed values for scaling of the Monte Carlo spectra.

A very good agreement of the background model with the data is achieved for the low energy region (<700 keV) and for the main peaks: ^{214}Pb (352 keV), ^{208}Tl (583 keV), ^{137}Cs (662 keV), ^{60}Co (1173 and 1332 keV), and ^{40}K (1460 keV). This result confirms the validity of the background model presented in this work. The disagreement between simulated and measured spectra at high energies (above ~ 1.5 MeV) is caused by non-linear effects in the PMT response, which results in a worse performance of the position reconstruction algorithms, changing the rate in the fiducial volumes and leading to a worsening of the position dependent signal corrections. Another discrepancy is present in the energy range 700-1100 keV.

The cosmogenic activation of natural xenon during storage at Earth's surface might be responsible for this discrepancy. Therefore, it has been studied assuming 1 year of activation and 2 years of cooldown time with the ACTIVIA [17] and COSMO [18] simulation packages. Both use semi-empirical formulae [19] to estimate the cross-sections of nuclear processes. However, for some isotopes, the production rates predicted by the packages differ by one order of magnitude and more. A similar calculation has been performed for a natural xenon target in ref. [20] using the TALYS code [21], and the published results do not agree with either ACTIVIA or COSMO in terms of isotopes produced by cosmogenic activation and their production yields. These disagreements make a quantitative analysis of this possible background source difficult, and do not allow a reliable prediction. In addition, some isotopes from activation (such as ^3H) might be removed by xenon purification [20].

The theoretical spectrum of the 2ν double beta decay of ^{136}Xe is also shown in Figure 10, assuming the half-life limit of $>1.1 \times 10^{22}$ years [15]. Its contribution does not change the total background spectrum significantly, thus it can be concluded that the observed discrepancy

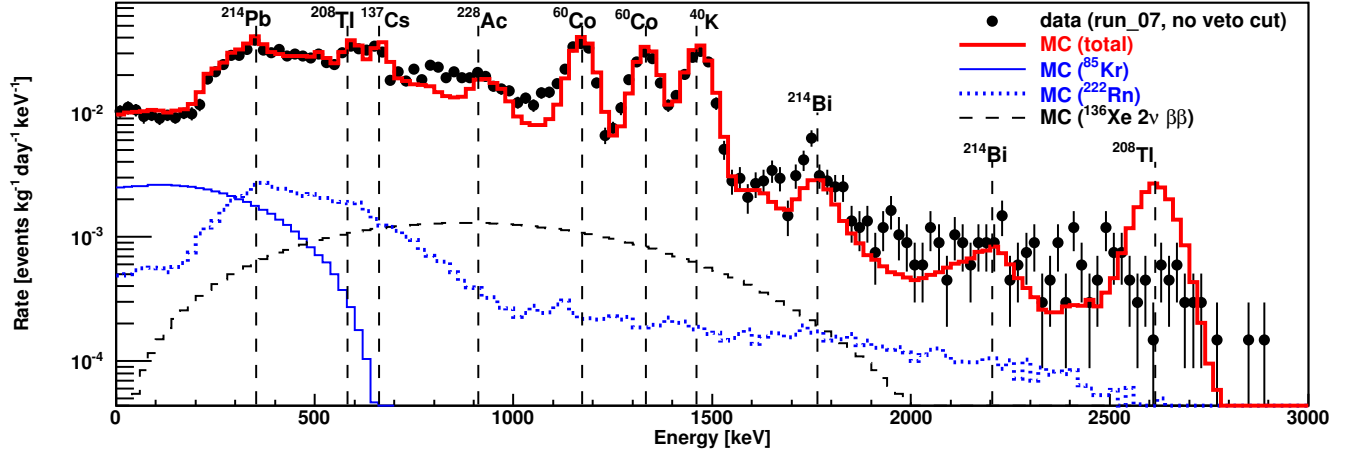


FIG. 10: (Color online) Energy spectra of the background from real data (first science run_07 [5]) and Monte Carlo simulations in the 30 kg fiducial volume without veto cut (thick red solid line). Cosmogenic activation of LXe is not included. The energy spectra of ^{85}Kr and ^{222}Rn decays in LXe are shown with the thin blue solid and dotted lines, respectively. A thin black dashed histogram corresponds to 2ν double beta decay of ^{136}Xe , assuming the half-life limit of $>1.1 \times 10^{22}$ years [15].

TABLE IV: Summary of the electronic recoil background (single scatter events in the energy range 0-100 keV) before S2/S1 discrimination. An average energy threshold of 100 keV is assumed for the veto cut.

Volume	Predicted BG rate [$\times 10^{-3}$ events $\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$]					
	target (62 kg)		fiducial (40 kg)		fiducial (30 kg)	
Veto cut	none	active	none	active	none	active
Detector and shield materials	136.8	75.2	12.9	3.4	7.2	2.00
^{222}Rn in the shield (1 Bq/m ³)	6.0	1.7	0.9	0.2	0.2	0.02
^{85}Kr in LXe (150 ppt of ^{nat}Kr)	2.9	2.9	2.9	2.9	2.9	2.90
^{222}Rn in LXe (21 $\mu\text{Bq/kg}$)	1.1	0.5	0.6	0.4	0.5	0.36
All sources	146.8	80.3	17.3	6.9	10.8	5.3

around 700-1100 keV cannot be explained by this potential background source.

VIII. CONCLUSIONS

A detailed Monte Carlo study has been performed in order to predict the electronic recoil background of the XENON100 experiment. The study is based on the Monte Carlo simulations with GEANT4 using a detailed mass model of the detector and its shield, and the measured radioactivity values of most components.

The design goal of XENON100, i.e. to gain a factor of 100 reduction in background rate, compared to that of XENON10 ($0.6 \text{ events}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ [3]), has been achieved. This has been possible thanks to a selection of all detector materials, an innovative coupling of the cryogenic system, the use of an active LXe veto and an improved passive shield.

The predicted upper limit on the average single scatter electronic recoil rate in the energy region of interest (0-100 keV) without an active veto veto is

17.4×10^{-3} and $10.9 \times 10^{-3} \text{ events}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ for 40 kg and 30 kg fiducial mass, respectively (Table IV). By applying a veto cut with an average energy threshold of 100 keV, these rates are reduced to 7.0×10^{-3} (5.4×10^{-3}) $\text{events}\cdot\text{kg}^{-1}\cdot\text{day}^{-1}\cdot\text{keV}^{-1}$ for 40 kg (30 kg) fiducial mass. The discrimination between electron and nuclear recoils based on the ratio of proportional to primary scintillation light (S2/S1) is not considered in this paper, and gives a further background reduction of $>99\%$.

From the good agreement between MC and data, as shown in Figure 10, and the predicted background rates from Table IV, it can be concluded that the electronic recoil background in the XENON100 experiment during run_07 is dominated by the natural radioactivity in the detector materials. With an optimized fiducial volume cut and an active veto cut, the background rate in the energy region of interest can be reduced down to a level where radioactive ^{85}Kr in LXe starts to dominate. However, the ^{85}Kr contribution can be further reduced by LXe purification.

The results of the present work are not only important

for understanding the electromagnetic background in the XENON100 experiment and the validation of the background model, but can be also useful for the design of the next generation detectors for dark matter searches.

IX. ACKNOWLEDGEMENTS

This work has been supported by the National Science Foundation Grants No. PHY-03-02646 and

PHY-04-00596, the Department of Energy under Contract No. DE-FG02-91ER40688, the CAREER Grant No. PHY-0542066, the Swiss National Foundation SNF Grant No. 20-118119, the Volkswagen Foundation, and the FCT Grant No. PTDC/FIS/100474/2008.

-
- [1] J.D. Lewin and P.F. Smith, *Astropart. Phys.* **6** 87 (1996); G. Jungman, M. Kamionkowski, and K. Griest, *Phys. Rept.* **267** 195 (2006).
 - [2] E. Aprile *et al.* (XENON10 Collaboration), arXiv:1001.2834v1 (2010).
 - [3] J. Angle *et al.* (XENON10 Collaboration), *Phys. Rev. Lett.* **100** 021303 (2008).
 - [4] J. Angle *et al.* (XENON10 Collaboration), *Phys. Rev. Lett.* **101** 091301 (2008).
 - [5] E. Aprile *et al.* (XENON100 Collaboration), *Phys. Rev. Lett.* **105** 131302 (2010).
 - [6] J. Sulkimo *et al.* GEANT4 Collaboration, *Nucl. Instrum. Methods Phys. Res. Sect. A* **506** 250 (2003).
 - [7] M. Yamashita *et al.*, *Nucl. Instrum. Methods Phys. Res. Sect. A* **535** 692 (2004).
 - [8] Hamamatsu Photonics, private communication.
 - [9] R.A. Muller *et al.*, *Phys. Rev. Lett.* **27** 532 (1971).
 - [10] O. Cheshnovsky *et al.*, *Chem. Phys. Lett.* **15** 475 (1972).
 - [11] L. Baudis *et al.*, 'The Gator low-level counting facility and material screening results'. Manuscript in preparation.
 - [12] C. Arpesella, *Appl. Radiat. Isot.* **47** 991 (1996).
 - [13] E. Aprile *et al.*, 'Material screening and selection for the XENON100 experiment'. Manuscript in preparation.
 - [14] D. Smith and N. Weiner, *Phys. Rev. D* **64** 043502 (2001); S. Chang *et al.*, *Phys. Rev. D* **79** 043513 (2009).
 - [15] R. Bernabei *et al.*, *Nucl. Phys. B* **110** (Proc. Suppl.) 88 (2002).
 - [16] E. Conti *et al.*, *Phys. Rev. B* **68** 054201 (2003); T. Doke, *NIM* **B234** 203 (2005); E. Aprile *et al.*, *Phys. Rev. B* **76** 014115 (2007).
 - [17] J.J. Back and Y.A. Ramachers, *Nucl. Instrum. Methods Phys. Res. Sect. A* **586** 286 (2008).
 - [18] J. Martoff and P.D. Lewin, *Comput. Phys. Commun.* **72** 96 (1992).
 - [19] R. Silberberg and C.H. Tsao, *Astrophys. J. Suppl.* **220** 315 (1973); R. Silberberg and C.H. Tsao, *Astrophys. J.* **501** 911 (1998).
 - [20] D.M. Mei, Z.B. Yin, and S.R. Elliott, *Astropart. Phys.* **31** 417 (2006).
 - [21] A.J. Koning, S. Hilaire, and M. C. Duijvestijn, *AIP Conf. Proc.* **769** 1154 (2005).